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Published in:
Geosciences

DOI:
10.3390/geosciences8020045

Publication date:
2018

Citation for published version (APA):
Hallouin, T., Bruen, M., Christie, M., Bullock, C., & Kelly-Quinn, M. (2018). Challenges in using hydrology and water quality models for assessing Freshwater Ecosystem Services: A Review. Geosciences, 8(2), [45]. https://doi.org/10.3390/geosciences8020045

geosciences

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Review

Challenges in Using Hydrology and Water Quality Models for Assessing Freshwater Ecosystem Services: A Review

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Received: 1 November 2017; Accepted: 12 January 2018; Published: 27 January 2018

Abstract: Freshwater ecosystems contribute to many ecosystem services, many of which are being threatened by human activities such as land use change, river morphological changes, and climate change. Many disciplines have studied the processes underlying freshwater ecosystem functions, ranging from hydrology to ecology, including water quality, and a panoply of models are available to simulate their behaviour. This understanding is useful for the prediction of ecosystem services, but the model outputs must go beyond the production of time-series of biophysical variables, and must facilitate the beneficial use of the information it contains about the ecosystem services it describes. This article analyses the literature of ad hoc approaches that aim at quantifying one or more freshwater ecosystem services. It identifies the strategies adopted to use disciplinary-specific models for the prediction of the services. This review identifies that hydrological, water quality, and ecological models form a valuable knowledge base to predict changes in ecosystem conditions, but challenges remain to make proper and fruitful use of these models. In particular, considerations of temporal and spatial scales could be given more attention in order to provide better justifications for the choice of a particular model over another, including the uncertainty in their predictions.

Keywords: freshwater resources; ecosystem services; hydrology; water quality; modelling

1. Introduction

Earth's ecosystems provide many services to human societies [1], recognised in the concept of ecosystems services described in the Millennium Ecosystem Assessment [2] as enhancing "the conservation and sustainable use of ecosystems and their contributions to human well-being".

In many regions of the world, human settlements and activities have converted pristine natural areas for urbanisation and agricultural purposes, resulting in natural habitats fragmentation and biodiversity loss [3,4]. These human-induced changes have impacted ecosystems and their potential to provide services [5]. However, the human population itself is an integral part of the environment, so any threat to environmental sustainability is also a threat to human welfare [6]. The ecosystem services concept can help in managing this threat: for instance, it can be used to demonstrate the current dependence of the humans on ecosystems [7,8], it can be used to understand how the human activities are currently impacting ecosystems [9–11], and it can be used to quantify the benefits of ecosystem restoration measures [12,13]. Conversely, the study of ecosystem services could be detrimental: for instance it can be used to commodify nature [14], and it can be used to optimise the delivery of the services perceived as essential, to the neglect of others, i.e., not looking at the full picture. For example, the supporting services found in the adaptive capacity of freshwater ecosystems to mitigate some climate change effects and other future pressures is often overlooked in favour of direct uses of the water resources for consumption or irrigation [15].

In most regions of the world, the security of freshwater resources is under high levels of threat, particularly from intensive agriculture and urbanisation [16]. Freshwater resources are key elements in the provision of many ecosystem services. Indeed, the hydrological cycle is intimately linked with many environmental processes that are essential for human welfare including, among others, the provision of safe water from surface and subsurface water bodies, rain-fed or irrigated agricultural production, or aquaculture. Beyond these tangible aspects, freshwater resources also support many cultural services, including navigation, recreational activities such as angling and water sports, and areas of aesthetic beauty and spiritual value.

Investigating the impacts of environmental changes such as agriculture intensification, urban expansion, and climate change requires an understanding of the relationship between landscape configurations and management strategies, and their impacts on freshwater ecosystems and their services. Field experiments and data sampling, in combination with computational models can contribute to appreciating the complexity of freshwater ecosystems and the main drivers of their functioning and malfunctioning. This understanding will be crucial to inform decision makers on the main measures required to preserve and restore freshwater ecosystems.

Some specially designed ecosystem services models are available that include the contribution of some freshwater ecosystem services, e.g., InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) and ARIES (ARtificial Intelligence for Ecosystem Services). However, most of the biophysical aspects underlying these services can also be quantified by existing models, either from hydrological and/or ecological disciplines, and there is a presumption that bespoke modelling frameworks making use of such models are more accurate than generic ecosystem services models in predicting the provision of freshwater ecosystem services. Here, we question whether the use of such discipline-specific models is sufficient to quantify ecosystem services, and if their higher complexity is exploited if at all, and call for a consistent use of hydrological and water quality models in assessing freshwater ecosystems services. This review is primarily intended for both ecosystem services practitioners more used to using generic models, and hydrological modellers interested in making a wider use of their models. We start by introducing the various existing concepts identified as essential for considering and modelling freshwater ecosystem services, including the concept of blue water and green water, the associated hydrological attributes, and the use of the catchment as an appropriate scale of analysis to avoid unintended trade-offs. Subsequently, we review the existing ad-hoc modelling approaches focussing on how they model hydrological processes for freshwater ecosystem services. Finally, the discussion section identifies the main trends and current shortcomings, and makes some recommendations for future research.

1.1. Definition of Freshwater Ecosystem Services

Ecosystem services related to water can take three forms: hydrological, aquatic and marine ecosystem services [17] as illustrated in Figure 1. They are provided by terrestrial, freshwater and marine ecosystems, respectively. Since they are all closely connected through the hydrological cycle, modification of one will affect the others. In order to describe the concepts and methods for maintaining freshwater resources, the focus is on hydrological and aquatic ecosystem services provided by terrestrial and freshwater ecosystems, representing the landscape—the seascape is not involved in the freshwater processes considered here, although it may be affected by the quality of freshwater reaching the estuaries. Together, hydrological and aquatic services form the concept of freshwater ecosystem services.

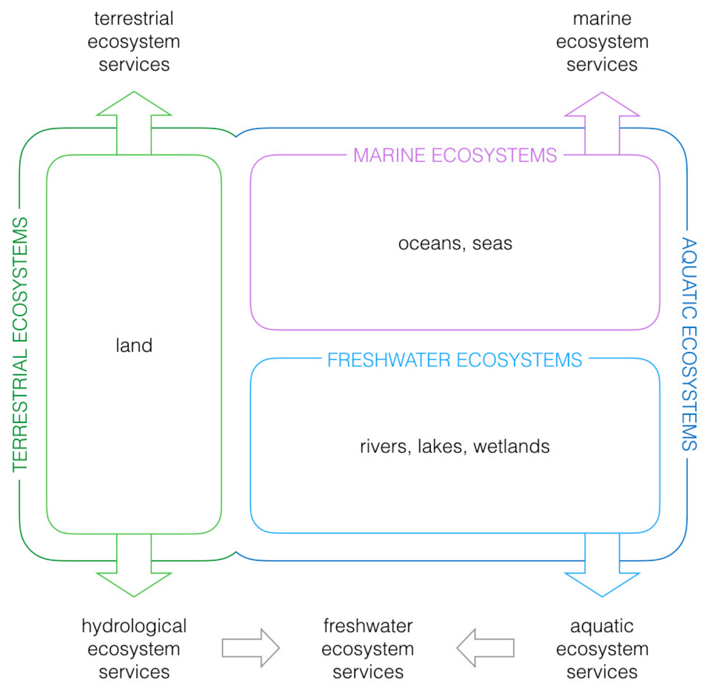

Figure 1. The variety of ecosystem services in the landscape and seascape.

Hydrological Ecosystem Services are the functions of the terrestrial ecosystems (land) affecting freshwater that benefit human beings [18]. They are a subset of the terrestrial ecosystems services [17]. Aquatic ecosystem services are the freshwater ecosystems (rivers, lakes, wetlands) functions benefiting human beings. And marine ecosystem services are the functions of the marine ecosystems (seas, oceans) that benefit people.

Terrestrial ecosystems will be the main direct receivers of precipitation because of their much bigger surface area compared to freshwater ecosystems (rivers and lakes). However, terrestrial ecosystems also provide a medium through which a fraction of this freshwater flows to rivers and lakes, home of freshwater ecosystems and also affects the quality of the freshwater (both purification and contamination) and the timing of flows towards other remote potentials users. These actions support the supply of (clean) freshwater for a large geographical area, that is the catchment. They represent a first set of freshwater services, where the flow of water is a final ecosystem service, i.e., outcome from the ecosystems directly benefitting people [19].

The terrestrial and freshwater ecosystems also shelter a variety of organisms (flora and fauna) involved in the delivery of services supported by freshwater (as a resource or as a living environment). They represent a second set of freshwater services, where the flow of water is an intermediate service, i.e., process supporting final ecosystem services [2].

1.2. Green Water/Blue Water Concept

Terrestrial ecosystems receive limited amounts of water through precipitation that is subsequently partitioned between all the users' needs within the catchment, i.e., the ecosystems and the humans [20]. Beyond the hydrological "loss" through evaporation, this partitioning is between three pathways: uptake of moisture from the soil by plants for transpiration (e.g., trees, crops), direct runoff into rivers and lakes, and recharge of groundwater reserves. The use of freshwater for any one of these needs implies a reduction of freshwater for the others. Stormflow (direct runoff for rapid supply) and base flow (groundwater recharge for delayed supply) form the concept of blue water: which is the amount of rainfall exceeding soil capacity that will supply rivers, lakes and aquifers. The concept of green water corresponds to the amount of rainfall infiltrated and temporarily stored in the root zone of the soil that will be used for primary production of natural and agricultural systems [21].

Ecosystem services linked to blue water are manifold, including water supply for drinking, for hydropower production, or as an ecological habitat. Green water is also essential for many services provided by e.g., rain-fed agriculture or forestry. The use of freshwater resources as green water decreases the availability for blue water. Trying to improve one might represent a trade-off for the other. This is why, in ecosystem services management, they should always be considered simultaneously. Land management decisions can influence the partition of rainfall between green and blue water [21]. In fact, land use, ecosystem and water management should form an integrated approach to landscape management since they are interlinked, and decisions on one of these aspects will have effects on the others [20]. For instance, evapotranspiration represents a trade-off between terrestrial ecosystems needing water for photosynthesis (transpiration) with associated non-productive loss (evaporation), and freshwater ecosystems needing water to support aquatic life in the first place, and other forms of life after abstraction; and the rate of evapotranspiration is influenced by land cover (e.g., vegetation index) and the land use (e.g., forestry) [22].

In the management of freshwater resources, green water could only be seen as a loss with regard to the supply of freshwater in rivers and lakes. While vegetation is considered to have a beneficial action on this water supply because of its impacts on water infiltration and percolation in the soil matrix, it should not be forgotten that, at the same time, vegetation is a water user as well. And, while not providing directly water related ecosystem services, it provides other ecosystem services such as the supply of material or food (wood or crop biomass), not mentioning the uptake of some of the contamination carried in the water. Therefore, studying the supply of aquatic ecosystem services without considering these hydrological ecosystem services ignores potential hidden trade-offs and synergies. This association aims at covering the initial use of freshwater before reaching the freshwater ecosystem (e.g., as a resource), the use of freshwater for in-stream processes (e.g., as a living environment, as a solvent, as a medium for transport), and the subsequent use of freshwater (e.g., as a resource for drinking or irrigation).

As advocated by Baron, et al. [15], freshwater (aquatic in the original text) ecosystems are strongly connected to terrestrial ecosystems; rivers should not be considered only as conduits for water supply, as in some water resources management approaches. This is in line with the concept of Integrated Land and Water Management [23].

Thus, the concepts of green and blue water are intrinsically associated with water quantity issues. It does not explicitly cover water quality problems, although the amount of water reaching rivers will affect their ability to dilute pollutants.

1.3. Hydrological Attributes as a Basis for Composite Indicators

The effect of terrestrial ecosystems on freshwater resources can be characterised using four attributes: quantity, quality, location, and timing. The combination of these attributes defines hydrological ecosystem services [18]. They represent the dimensions in which the terrestrial ecosystems can affect freshwater.

A terrestrial ecosystem can affect water quantity by influencing the elements of the water balance (e.g., streamflow in downstream rivers, evaporation rates, soil moisture). It can affect water quality by releasing or retaining pollutants (e.g., nutrients, sediments, pathogens), and by treating pollution (e.g., denitrification). The effects of water quantity and quality will have different impacts on the provision of ecosystem services, depending on the location and timing of these effects. The location (e.g., upstream/downstream, aboveground/belowground) is important to determine if the beneficiaries will be affected by the change of quantity/quality (e.g., water accessibility, flooding areas, sources of pollution downstream not affecting upstream areas). The timing is also important because the change of quantity/quality may or may not be useful for the beneficiaries whether it coincides in time with their needs or not (e.g., in period of vulnerability, in the growing season for crops, or in dry season for domestic water supply), or, on the other hand, whether the sudden landscape response to extreme rainfall impedes human capacity for adequate response (e.g., evacuation before flooding events).

The impacts on freshwater represented by the hydrological ecosystem services and described by the hydrological attributes will, in turn, affect the aquatic ecosystem services (as defined in Figure 1). Some aquatic ecosystem processes will only be a spatial displacement of hydrological services to a different location (e.g., non-drinking water supply), some will be a spatial displacement of the absence of hydrological services (e.g., nutrients/sediments not retained in land, transported along rivers), some will be a consequence of hydrological services as their drivers (e.g., water supply providing living environment for aquatic biota, nutrient concentration affecting eutrophication, sediment concentration affecting undesirable deposition on river beds, pollution affecting aquatic life, pollution affecting rivers as a cultural amenity), and some will be a treatment of the hydrological services supplied (e.g., nutrient uptake by aquatic biota). The aquatic ecosystem services due to hydrological services are a combination or direct translation of any of these processes.

These hydrological attributes can be used to determine the requirements of the freshwater ecosystems themselves in terms of adequate conditions that support the processes and properties preserving their continued integrity [15].

2. Research Aims and Methods

2.1. Research Aims

The objective of this review is to describe the current state-of-the-art of ad-hoc modelling approaches for the characterisation of freshwater ecosystem services, while including hydrological considerations. A conceptual representation of the embedding of biophysical models for freshwater ecosystem services modelling is proposed in Figure 2. The biophysical models are expected to be used to capture the key behaviour of the environmental system that are relevant for a given freshwater ecosystem service. In this review, we focus on the modelling of environmental system, as represented on the left-hand side in Figure 2.

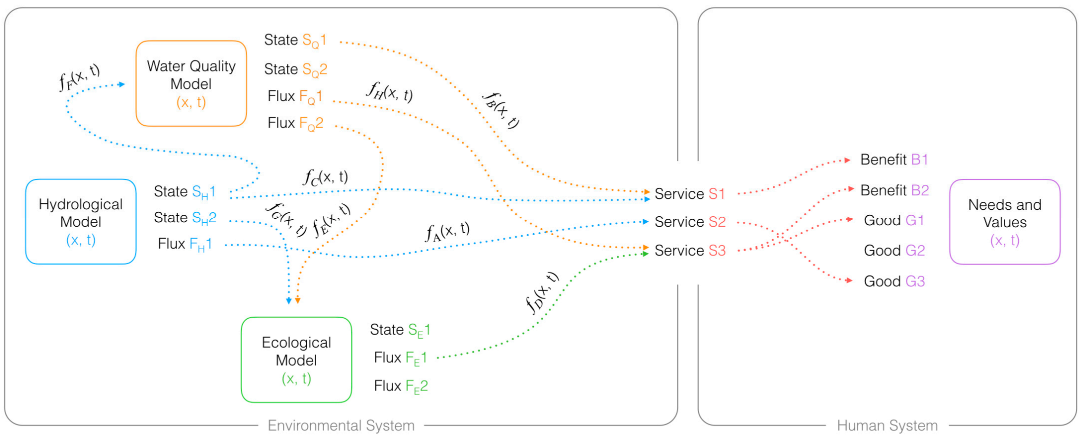

Figure 2. A conceptual representation of the articulation of biophysical models used to predict the provision of freshwater ecosystem services (where x represents the spatial dimension, and t the temporal dimension).

Biophysical models feature their own spatial and temporal dimensions, and can be either multi-disciplinary (hydrology and/or water quality and/or ecology), or also can be specific to a particular discipline, where often many models are available tailored to specific purposes, and hence having their specific spatial and temporal scales. On the other hand, freshwater ecosystem services have their own spatial and temporal dimensions (characterised by the hydrological attributes) that is correlated to human needs and values. This potential mismatch requires that modellers/practitioners decide what spatial and temporal scales are suitable for the study area and the ecosystem services at stake. This is conceptually represented on Figure 2 by the links between models and services characterised by functions with time and space dimensions.

Moreover, the provision of freshwater ecosystem services may only rely on specific aspects (given states and/or fluxes) considered within the biophysical models. This will again require some decisions from the modellers/practitioners in order to select the relevant model outputs. This is conceptually represented on Figure 2 by the presence of links between models and services only for some, not all, model states and fluxes.

This review focuses on the type of biophysical models being used to address the quantification of freshwater ecosystem services. It aims at identifying how biophysical model outputs have been translated into/linked to ecosystem services. Of particular interest in this review are the considerations of hydrological temporal and spatial scales (following the hydrological attributes of Brauman, et al. [18]), and whether the complexity (level of detail) of the hydrological models has been summarised to match the temporal and spatial scales of the ecosystem services.

Purposely developed ecosystem services models are not included in this review, and the reader can refer to a thorough review of these models proposed by Bagstad, et al. [24]. However, these generic models also cover the environmental system, as defined in Figure 2, so they will be mentioned in the Discussion section to compare their approaches with ad-hoc approaches.

In some of these generic models, ad-hoc approaches include valuation aspects. Whether economic or not, valuation exercises provide information about the importance of given ecosystem services for people, in many different forms and at many different scales [25]. Valuation can inform the identification of the biophysical characteristics of the ecosystems that people value most, hence helping in selecting the model states and/or fluxes of relevance for given ecosystem services. However, this review focuses on the biophysical characteristics effectively selected in modelling approaches, and it does not consider whether valuation influenced this selection.

2.2. Methology Used for the Review

A literature survey was conducted on the 14th of December 2016 on the database Web of Science, looking for all the publications in English published between 2005 and 2016 with the keywords "freshwater ecosystem(s) service(s) model". All peer-reviewed articles have been included, while books were excluded from the review. The cut-off at 2005 was decided to include the millennium assessment period, while older approaches would not be considered as representative of current best practices in freshwater ecosystem services modelling. A total of 415 articles were found in the database.

The first stage of screening involved looking at the title of the articles to identify the ones that did not focus on freshwater. This meant titles mentioning coast, estuary, sea, lagoon, bay, ocean, tidal or marine were not included. Any paper whose title did not mention any of these terms was kept for the next screening stage. Forty-five papers were eliminated by this first screening. Four duplicate papers were also removed.

The second stage of screening involved reading the abstracts of all the remaining papers to identify whether they focused effectively on freshwater, on ecosystem services, and on modelling simultaneously:

- 34 papers were excluded because they focused solely on ecosystem services valuation, whether through economic valuation or stakeholder's preferences evaluation;
- 14 papers were excluded because they were not dealing with freshwater resources (they were not eliminated from the first screening because it was not obvious from the title);
- 18 papers were eliminated because they were not dealing with ecosystem services or service capacities, even loosely;
- 206 papers were finally excluded because they did not focus on modelling activities.

If the abstract was not detailed enough to determine whether it should be kept for the next stage of the literature review, the full paper was consulted to make the final decision.

In the end, 94 papers were identified as potentially covering the scope of this review and all were analysed. Among these, nine of them relied on existing mainstream ecosystem services models (e.g., ARIES, InVEST). From the 85 remaining full papers read, 41 were analysed further. The remaining papers did not cover the scope of this review, either because not enough information was provided on the modelling aspects or because they did not cover explicitly hydrological aspects and were not considered further.

3. Results

In this section, an analysis of the reviewed articles is provided, starting with an overall comparison of the geographical distribution of the research efforts in the field of freshwater ecosystem services modelling, as well as the types of waterbodies and biophysical aspects considered. Then, these studies are thematically compared and regrouped into three categories: water quantity (availability) related ecosystem services, water quality related ecosystem services, and ecology related ecosystem services. Finally, the modelling approaches used for the hydrology are compared with respect to the research objectives outlined above. All the information summarised in the Figures of this section can be found in the Supplementary Material Table S1 available online.

3.1. Overall Picture of the Reviewed Literature on Freshwater Ecosystem Services Modelling

The geographical distribution of the modelling studies identified in this review is presented in Figure 3. The majority of the studies were concentrated in North America, mainly in the United States. The second most studied areas where Freshwater Ecosystem Services have been modelled were in Europe and Asia, each represented by a similar number of studies. Africa and South America have received less attention to date in this very specific field of research. Noteworthy, three large scale studies are also reviewed, two pan-European and one pan-African (identified in grey on the bar chart of Figure 3, not geographical represented). This geographical demonstrates the variety of climatic regions covered by the reviewed studies and it was expected that this would influence the focus of the studies, e.g., on water supply security in arid regions.

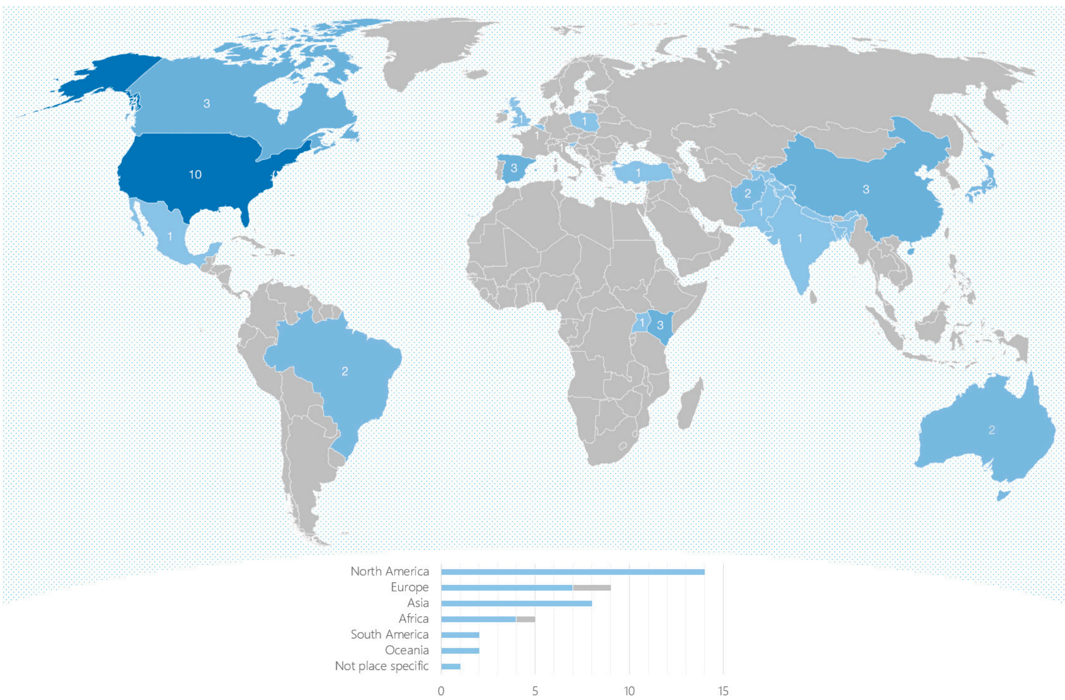

Figure 3. Geographical distribution of the reviewed studies modelling Freshwater Ecosystem Services.

In the literature reviewed, a majority of studies (24) considered ecosystem services associated with Blue Water, mostly alone (see Figure 4A). However, a significant number (15) considered freshwater ecosystem services linked to both Blue and Green Water (as defined in Section 1.2). Figure 4B shows that many studies (22) focused on one biophysical aspect, whether water quantity, water quality, or ecology. Integrated studies looked at several biophysical aspects in combination, mostly two (15), less frequently all three (4), i.e., water quantity, water quality, and ecology. Finally, Figure 4C indicates that the vast majority of studies reviewed (20) focussed on the whole river basin for their study (i.e., terrestrial ecosystems), indicating a higher proportion of hydrological ecosystem services than aquatic ecosystem services. However, aquatic ecosystem services were considered as well, either alone when the focus was on the waterbody itself, or in integrated land and water management studies where both basin and water body were considered.

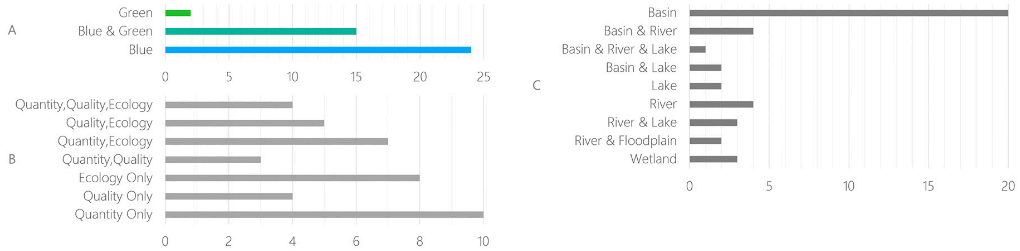

Figure 4. Comparison of the studies on: (**A**) Blue and/or Green Water being considered; (**B**) Biophysical aspects considered for the Freshwater Ecosystem Services studied; (**C**) Freshwater bodies under investigation.

Figure 5 presents an overall comparison of the studies on six key aspects: the method used to represent hydrology (quantitative or qualitative, measured or modelled), the characteristics of the hydrograph used to infer the provision of ecosystem services, the spatial and temporal resolution of the hydrological model, and the spatial and temporal scales extracted from the model outputs to infer the provision of ecosystem services. The studies were classified into seven categories depending whether they consider water quantity and/or water quality and/or ecology related freshwater ecosystem services. These aspects are discussed in a detailed manner in the following sub-sections before discussing the findings in the following Discussion section.

Figure 5. Comparison of the studies on their considerations of the hydrological cycle: (**A**) Method used to consider hydrology; (**B**) Aspects of the hydrograph linked to the ecosystem services; (**C**) Spatial scale of the hydrological model; (**D**) Spatial resolution used for the ecosystem services analysis; (**E**) Temporal resolution of the hydrological model; (**F**) Temporal scale used for the ecosystem services analysis.

It should be noted that no study used different hydrological models when considering different freshwater ecosystem services. This is why integrated studies could be gathered under a single category on Figure 5 when the considerations on hydrology were compared. Moreover, if categories did not include "quantity" on Figure 5 this did not mean that the hydrology was not considered; this only meant that hydrology was not used to quantify the provision of a final ecosystem service.

3.2. Water Availability Related Freshwater Ecosystem Services

In the reviewed literature, freshwater quantity was often modelled to consider the ecosystem service of water provision. Cabello, et al. [26] looked at the sustainability of water management practices for continued provision of freshwater. Dile, et al. [27] studied the most suitable areas for harvesting ponds, while Karabulut, et al. [28] studied where water scarcity could arise. Rodrigues, et al. [29] also considered the issues of water scarcity, both for blue and green water. Erol and Randhir [30] and Glavan, et al. [31] studied the impact of different land use on the availability of freshwater as surface water and groundwater.

Many studies looked at the repartition between water provided as discharge (blue water) and as soil moisture for vegetation evapotranspiration (green water) [21,32–35]. The study of the hydrological cycle and, in particular, infiltration, transpiration, runoff, and groundwater recharge could account for these services and can explain the trade-offs in managing freshwater resources.

Moreover, water quantity has been considered in ecosystem services related to flood risk mitigation, [36] and the balance between drinking water supply services and water for hydropower production services [37].

3.3. Water Quality Related Freshwater Ecosystem Services

The quality of freshwater available for sustainable use is intimately linked to the flow (renewal) of freshwater, its pathways (that determine what pollution the water will be in contact with), its residence time (determining for how long the pollution will be in contact with a specific landscape characteristic), and in terms of the quantity of water (determining the concentration of pollution given a load applied, dilution effect). It is then essential to consider the hydrological cycle as an important component when modelling the water quality related freshwater ecosystem services. Moreover, in addition to physicochemical characteristics of the landscape that can mitigate the origin and propagation of pollution, the ecology in contact with the pollution can also have mitigation effects, such as influencing pollution uptake or transformation (e.g., denitrification). In turn, by taking up this pollution, the ecological entities are affected, negatively (toxic substance, exceedance of algae negative for fish) or positively (food supply).

3.3.1. In the Aquatic Ecosystems

In the reviewed literature, the nitrogen cycle and loadings of nitrate on land were extensively studied when considering freshwater ecosystem services [38–42]. The phosphorus cycle, another notorious nutrient responsible for pollution in freshwater bodies, was associated with water quality related ecosystem services [39,40,42,43]. Dissolved oxygen [40], suspended matter [43], and ammonia and methylmercury [44] were also studied and modelled. All of these pollutants were investigated to assess the assimilation capacity and response of freshwater ecosystems.

Moreover, nutrients are also a supply of food for aquatic fauna and flora. Kaggwa, et al. [45] and Landuyt, et al. [46] considered the nitrogen cycle to assess the capacity of the ecosystem for fish production, in addition to the positive effect of this uptake on the water quality, similar to the studies highlighted above. Roy, et al. [47] studied the phosphorus cycle and its impacts on the ecology (dynamics of algae and zooplankton) in order to predict water clarity, used as a proxy for cultural services (aesthetics and recreation). In these studies, the water quality aspect was taken as an intermediate service.

For modelling the water quality, different types of models were used. Wagner and Zalewski [43] used a correlative approach based on field measurements in an attempt to infer an empirical regression equation between explanatory variables (hydrodynamics and air temperature) and response variables (phosphorus and suspended matter concentrations). Some studies used existing physical models to simulate the mass transfer and biochemical processes occurring in open waters [38,40]. However, most studies developed their own conceptual models to simulate the dynamics of pollutants in the freshwater bodies themselves. Some have used Bayesian Belief Networks to graphically depict their conceptual understanding of the dynamics of interest: Spence and Jordan [41] relying on measured datasets to train their network and evaluate the model, and Landuyt, et al. [46] relied on existing data and expert knowledge to populate the conditional probability tables. On the other hand, some other studies built their conceptual model and established the links between the variables using deterministic empirical equations sourced from the literature, and used data from the literature to calibrate the parameters of these equations [41,45].

The freshwater ecosystems considered for water quality related services were diverse: from in-stream dynamics in rivers [38,43] to dynamics in lakes [40,47], in ponds [45,46], and in wetlands [41].

3.3.2. In the Terrestrial Ecosystems

However, since the pollution found in water mostly originates from terrestrial regions, it was relevant to include the terrestrial realm as part of the case studies in water quality models. These services are termed hydrological ecosystem services [18], but can also be considered as part of the freshwater ecosystem services [48]. In the literature on freshwater ecosystem services mentioned above, the studies focusing on water quality rarely modelled the pollution pathway through the terrestrial ecosystems; rather they used measurements, standards, or published data of the pollution loading inputs. Johnston, et al. [44] was a valuable exception, and they proposed an integrated approach to modelling the water quality in terrestrial ecosystems and its impacts on the associated aquatic habitat.

To capture these terrestrial ecosystem services, it is necessary to include a water quality component to a hydrological model in order to account for the pollution propagation through the landscape and its potential attenuation (uptake, decomposition, etc.).

Included in these hydrological ecosystem services, erosion and the problems of sedimentation in rivers were studied to consider the hydrological ecosystem service of preventing soil erosion [27,30,42,44,49]. The problems of nutrient pollution in rivers due to diffuse agricultural sources were also studied in order to determine the capacity of the landscape to mitigate the transmission of diffuse source pollution toward the water bodies, including for nitrates [30,44,50,51] and for phosphates [30,44,50]. Erol and Randhir [30] also considered some point sources of pollution such as septic tanks. Other pollutants were considered: for example, Johnston, et al. [44] considered methylmercury to determine if the concentrations exceed the sanitary thresholds. Both mechanistic and conceptual models were considered for these hydrological ecosystem services. They could be used to predict the dynamics of the input to river (e.g., Johnston, et al. [44]) in order to provide a finer quantification of the pollution loadings to rivers compared to the studies mentioned before that focus on the dynamics within the waterbodies only. They could also be used to quantify the capacity of the landscape to mitigate the pollution before reaching the river (e.g., Kauffman, et al. [49]).

3.4. Ecology Related Freshwater Ecosystem Services

The water availability and the water quality can have impacts on the ecology, on both the fauna and the flora, within both terrestrial and aquatic ecosystems. Moreover, other environmental factors such as the water temperature or the presence of invasive species can affect the provision of ecology related freshwater ecosystem services. These include, among others, the provision of food (e.g., fish), or the opportunity for recreational activities (e.g., angling, water sports).

Any ecological study of a biota population that is used (consumed, fished, watched) by the human population can be considered a freshwater ecosystem services study to a certain extent.

In the literature on freshwater ecosystem services modelling, many studies have focused on fish populations: for example Boughton and Pike [52] studied the impacts of altered storm patterns on fish migration windows, Bouska, et al. [53] studied the impact of environmental changes on fish species distributions, Downing, et al. [54] focused on the effect of lake management on the stock of fish, Nelson, et al. [55] studied the impact of sediments, water flows and temperature on fish assemblages, and van Poorten, et al. [56] studied the effects of stocking management on the fish population. However, the fish dynamics depend mainly on the availability of food. For example, Nelson, et al. [55] used a food availability module in their model to take into account the dynamic relationships between the detritus, invertebrates, algae and prey fish in-stream. Other species have also been studied, such as macroinvertebrates [57] as well as vegetal assemblages [58,59]. van Dam, et al. [33] studied the multifunctional aspects of wetlands, including fish, livestock, and other agricultural production. Cluer and Thorne [60] looked at the impacts of different hydrogeomorphic configurations of streams on aquatic flora and fauna.

The methods used to cover ecology related ecosystem services could be categorised into correlative models and conceptual models. Both techniques were popular when modelling the ecological processes supporting freshwater ecosystem services. Correlative methods are models designed from simple to more complex statistical analyses on datasets in order to determine empirical relationships between explanatory variables (drivers) and response variables (services/functions of interest). Methods varied from Bayesian statistics on laboratory datasets [52], machine learning techniques applied to field measurements [53], to boosted regression trees [57]. Conceptual methods are models based on the mechanistic understanding of the ecological processes. They can be shaped as probabilistic models such as Bayesian Belief Networks [33,59] where the links between variables can be characterised with expert knowledge or from datasets. They can also be deterministic models where the links are characteristics by empirical equations from the literature [55,56]. More qualitative approaches can also be used, such as feedback diagrams where only the positive or negative character of the relationships between variables is expressed [54].

3.5. Hydrological Considerations

This sub-section assesses how the hydrology of the ecosystems and their dynamics have been included in the reviewed studies. To do so, the information contained in Figure 5 is used to identify whether trends and correlations exist within each combination of biophysical aspects considered, that is to say water quantity and/or water quality and/or ecology.

The majority of the studies reviewed modelled the hydrology, as seen on Figure 5A, rather than measuring the dynamics. However, when the ecosystem services considered included quality or ecology, alternative approaches were used. This was particularly the case when the study focussed on the waterbodies themselves; whether a river or lake. In these situations, flow measurements or flow regime categories (e.g., high flow, low flow) were sometimes considered sufficient.

Figure 5B displays the specific characteristics of the hydrograph that the studies focussed on. It was difficult to identify a strong trend, but the water budget was often of prime interest. Here, the water budget meant the repartition of precipitation between streamflow, groundwater recharge, soil moisture, and evapotranspiration. The flow variability, including here considerations such as the flashiness of a catchment or the river flow regime, was also of special interest in studies looking at water quality or ecology related ecosystem services. The total discharge (i.e., total volume of water discharged into river network for a given period) was also sometimes considered across all biophysical aspects. Another interesting characteristic of the hydrograph used in the reviewed studies was the minimum flow requirements, that could be important for continued water supply, but also for sustained ecological habitat conditions. Rodrigues, et al. [29] propose a valuable application of this principle.

Figure 5C shows the spatial scale considered when modelling the hydrology while Figure 5D shows what spatial scale is used when linking the hydrology with the ecosystem services in their analyses. The first insight was that when water quantity was considered, the spatial resolution was rather high (i.e., Hydrological Response Unit (HRU) or grid cell), except when water quantity and ecology were considered together. In this case, the spatial scale could vary more, mostly because the waterbodies themselves were often the focus in these cases, and the basin received less considerations; this was the same situation for water quality and/or ecology. HRU and grid cells were likely to be used for water quantity because the water budget was often of particular interest (see Figure 5B) where the location of the parcels mostly responsible ("hotspots") for one water flow or the other was considered. Such details are important for designing management measures.

For the analysis of the provision of freshwater ecosystem services (see Figure 5D), the spatial scales are often large, including results and comparisons summarised for the whole catchment, the whole river or the whole lake. However, when quantity and quality aspects are considered a finer scale is retained, e.g., sub-basins or land cover types. One study also used administrative boundaries to analyse the provision of the ecosystem services [61] which highlights the potential disconnect between the scales of the environmental system and those of the human system [25].

Finally, Figure 5E,F summarise the temporal resolution considered for the hydrology and its subsequent use for the analysis of the provision of ecosystem services. The use of a daily timestep for the hydrological modelling was widespread in the studies reviewed. This was likely to be due to the large availability of models and input data at this scale. One study even used hourly simulations for ecological considerations looking at fish migration windows accounting for durations in hours [52].

When linking hydrology and the provision of freshwater ecosystem services, Figure 5F shows that annual summaries were often used. This finding could be explained by the characteristic of the hydrograph presented on Figure 5B: when the total discharge was of interest, often an annual summary was the only information extracted from the hydrological outputs. On the other hand; when minimum flow requirements or flow variability was of interest, the temporal resolution was retained (whether daily or monthly) for the analysis of the provision of freshwater ecosystem services. Finally, seasonal summaries were also regularly considered for water quality and ecology related ecosystem services.

4. Discussion

4.1. Spatial Considerations

Freshwaters are a shared resource within the watershed, covering terrestrial and aquatic ecosystems, being used as green or blue water. However, many studies still focus on the use of blue water for human usage only. In areas where water resources are scarce, adding explicit considerations of green water should always be considered altogether to avoid biases in the assessment. This is precisely where the concept of ecosystem services can help in exhibiting the value of the ecosystems to humans in many different forms.

Guswa, et al. [62] argue that ecosystem services models are often used in land cover and land management scenarios, finding confirmed in many studies reviewed here focusing on hydrological ecosystem services. They also argue that the land-parcel is the level at which scenarios will be specified [62]. Thus, the hydrological models used need to be able to include this spatial heterogeneity properly. Many studies reviewed here were consistent with these recommendations, mostly due to the use of SWAT (Soil and Water Assessment Tool) and its fine spatial discretization (HRUs). However, this does not necessarily mean using a distributed model, the model should be only be able to account for the heterogeneity of the hydrological response of changing land cover in the catchment, and lumped models considering average land cover would also be impacted by a change in land cover. Semi-distributed models represent an intermediate alternative. It is argued that the spatial scale needs to be driven by the purpose of the study. In the reviewed studies, justifications for the choice the spatial discretisation scheme is lacking.

The considerations of spatial scale are also important for water quality related ecosystem services. Indeed, hydrological connectivity is not homogeneous across the catchment, and a same amount of nutrient applied in two different locations in the catchment could result in different levels of pollution in the river. Moreover, differentiation between dissolved and particulate forms of pollution requires a proper identification and modelling of the flow pathways through the catchment, over land, in the vadose zone, and in the saturated zone because they influence the biogeochemical reactions that the solute will be subject to [63]. However, if only water quantity is of interest, using such models could be unnecessarily complex with higher degrees of uncertainly than simpler, possibly lumped, models.

While the spatial scale is important to include both the complexity of the water movement through the landscape, and to include the heterogeneity of the system and its spatial variability drivers, it can also have an importance for the subsequent analysis of the modelling results. Guswa, et al. [62] argue that if spatial planning or payment for ecosystem services is the objective of the ecosystem service study, this spatial scale should be retained for the analysis. On the other hand, the comparison of scenarios could take it into account only implicitly by comparing the catchment scale outputs in a ranking approach. These recommendations are consistent with the reviewed literature. For example, Erol and Randhir [30] used a grid-cell hydrological model to compare annual catchment water budgets of different land cover scenarios, where such a fine spatial resolution might not have been required in this case. While Dile, et al. [27] used HRUs and SWAT for spatial planning of harvesting ponds, making full use of the high spatial resolution.

4.2. Temporal Considerations

The time step for streamflow simulations should be driven by the needs of the modelling exercise. For water resources management in the reviewed literature, annual total discharge or annual water budget are often considered sufficient for water supply studies, although in arid and semi-arid regions, with large seasonal contrasts in precipitation amounts, the dry season could be of particular interest. However, for ecological considerations, a finer time resolution is often considered to look at failures in meeting the environmental flow requirements for example. The situation can be similar for water quality considerations: annual export of nutrient is considered sufficient to characterise the impact of terrestrial land on aquatic ecosystems, while the aquatic biota might respond differently according to the daily or hourly dynamics of the pollution and this is the trend found in the reviewed literature. A prolonged medium level of pollution or a short-term high level of pollution could generate different effects on fish populations. However, the time step will be limited by the availability of data and suitable models. For example, daily precipitation is more widely available than hourly precipitation data.

In the literature on freshwater ecosystem services, the timing of the delivery of the service is indeed correlated to the service of interest, as mentioned above. However, daily simulations are also carried out when an annual water budget is the only interest of the analysis. Daily hydrological models often require more parameters to identify then annual models. This means that the uncertainty of the predictions could be increased due to a complexity of the model. In practice, a finer scale is often used to account for the non-linearities of the environmental system. It can also be driven by the scale at which the governing equations used by the model remain valid.

4.3. Ad hoc Approaches and Generic Ecosystem Services Models

In the literature on freshwater ecosystem services modelling, there is a variety of models used and hence a variety of services and indicators used. This makes comparisons between studies difficult. On the other hand, generic ecosystem services models such as InVEST or ARIES can be applied in many regions of the world, so that their applications can be compared for similar climatic zones, or across climatic zones. While these models use different indicators, they can also be compared between one another on some common ecosystem services. A study has recently quantitatively compared the results obtained from different generic models [64], although not focusing on freshwater ecosystem services only.

Moreover, many studies relied on the ecohydrological model SWAT to model freshwater ecosystem services, but since freshwater ecosystem services are not the main purpose of the model, different indicators and different focusses have been considered in these studies and comparisons remain difficult. Francesconi, et al. [65] provide a systematic review of the use of SWAT for ecosystem services and identify that it is mostly used to simulate regulating and provisioning services. Vigerstol and Aukema [48] compare hydrological and ecosystem services models and recommend choosing the model depending on the scope of the ecosystem services study (if non-water related services are required), the availability of data, and the availability of the required expertise in hydrology. However, in the reviewed literature, the choice of a model over another is rarely mentioned.

The decisions made in the choice of model components in generic ecosystem services models can inform the choice of discipline specific models for the quantification of freshwater ecosystem services. The developers of these generic models have selected biophysical models/components depending on the degree of complexity required to satisfactorily quantify the provision of the ecosystem service, and also that use only the available input data. For example, InVEST integrates two levels of model complexity in its hydrology component, one in its “water yield” and the other in its “seasonal water yield” models, because they are not intended to account for the same ecosystem services: hydropower production and water supply, respectively [66]. ARIES adapts the model complexity, that is the level of detail, depending on the input data available and the required connections with other biophysical models, using artificial intelligence parameterised with decision rules [67,68].

In this review, no study could be found using a similar philosophy, that is, different hydrological models to quantify different ecosystem services. The reasons for the choice of a particular model could not be found either. It is clear that the hydrological model with the finest temporal scale and the highest spatial resolution could allow for the quantification of many ecosystem services. It remains to be demonstrated, however, whether a one model fits all strategy should be preferred over a collection of one model per need, or in this case, one model per ecosystem service. An environmental model can only approximate the reality, and the degree of approximation depends on the purpose of the model. So, when a model originally developed for an alternative purpose is used for ecosystem services modelling, the suitability of the model is an important aspect to consider.

The study of all the services provided by a freshwater ecosystem (river, lake, wetland) will often require the use of a combination of models, in series or in parallel. Each ecosystem service can be characterised by a combination of the four hydrological attributes mentioned earlier. However, for each of these attributes, it is likely that different ecosystem services will require different levels of detail. This implies that the use of different models for different ecosystem services may be required, even when they are all influenced by the same variable, e.g., streamflow. Indeed, the increase of the level of complexity has often a cost on the level of confidence of the model predictions, increasing the complexity of a model should only be justified by the necessity to include more biophysical processes in the analysis, not because the model is able to run with the input data at hand.

4.4. The Multi-Criteria Problem

Modelling freshwater ecosystem services using biophysical models gives quantitative estimates of their provision, and when dealing with several ecosystem services, the model simulates situations where trade-offs between ecosystem services must be decided. In this case, it is not trivial to optimise such trade-offs and to determine if they are acceptable since they invariably prioritise some ecosystem services over others. This is why a model alone cannot be a complete decision support system (DSS) and an additional layer is necessary to reflect the importance of individual ecosystem services, even if only on a relative scale. This can be done using economic valuations, or using multi-criteria decision analyses (MCDA). However, these important considerations are beyond the scope of this review and the reader can refer to a recent review on Decision Support Tools for ecosystem services for more information on that aspect [69].

5. Conclusions

Freshwater ecosystem services cover a wide range of biophysical aspects spreading across hydrology and ecology, and are spatially distributed over terrestrial and aquatic ecosystem services. The literature on freshwater ecosystem services modelling covers very diverse objectives so that trends and best practices are difficult to identify. However, this diversity is also the opportunity to find many different innovative ways of extracting and summarising the information provided by biophysical models in order to quantify the provision of ecosystem services. Studies looking at sustained minimum flow requirements to maintain suitable habitat for stream ecology are a good example.

Here we also demonstrate the diversity of modelling approaches used to answer these objectives for freshwater ecosystem services, and are concerned that no study could be found that explicitly compared different available models for similar processes in order to justify the choice of a particular model. Especially in hydrology, there is a wide variety of rainfall-runoff models that can be used for ecosystem services studies. Comparative studies would be useful to determine the degree of complexity (physical description, spatial and temporal resolutions) that is truly required to accurately predict changes in ecosystem services. In particular, the comparison of their level of uncertainty would be valuable to be able to claim with a certain level of confidence that two scenarios are sensibly different given the predictive uncertainty.

The breadth of freshwater ecosystem services covered in a modelling study is crucial when used in a decision-making process. Indeed, omitting services could overlook trade-offs between competing services. This is why integrated modelling approaches are recommended to explicitly account for these trade-offs. This will require the use of models capable of representing all these services and it remains unclear whether a one-model-fits-all is preferable over a collection of purpose specific models. This review demonstrates that both integrated ecohydrological models such as SWAT have been used as well as bespoke combination of discipline specific models. But the lack of considerations for uncertainty in the predictions does not help in comparing the benefits of one over the other.

Ecosystem service valuation approaches were not covered in this review. However, they can be used in association with biophysical modelling approaches such as the ones reviewed in this manuscript. They allow for the inclusion of the importance of the various ecosystem services, as well as their accessibility to the beneficiaries. In addition, valuation can help in deciding what characteristics of the biophysical time series are crucial in quantifying the services, in addressing the challenges of going beyond biophysical quantities.

Supplementary Materials: The following are available online at www.mdpi.com/2076-3263/8/2/45/s1, Table S1: Summary of the information collected to compare practices in the reviewed articles.

Acknowledgments: The authors would like to thank Ireland's Environmental Protection Agency (EPA) for their financial support to the project ESManage (2014-W-LS-5). The authors thank the three anonymous reviewers for their comments that helped to improve this manuscript.

Author Contributions: Michael Bruen and Thibault Hallouin conceived the idea, planned the scope, produced a draft manuscript, and oversaw the production of subsequent revisions and the final manuscript. Thibault Hallouin assembled, reviewed, and categorised the literature. Mary Kelly-Quinn conceived and directed the overall research project, checked and reviewed the ecological/biological aspects of the manuscript. Mike Christie and Craig Bullock checked and reviewed the social sciences aspects of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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